Case Study:
Large Meteoroid Impact on the Moon on 17 March 2013

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Overview

On 17 March 2013 at 03:50:54 UTC, NASA detected a bright impact flash on the Moon caused by a meteoroid impacting the lunar surface.

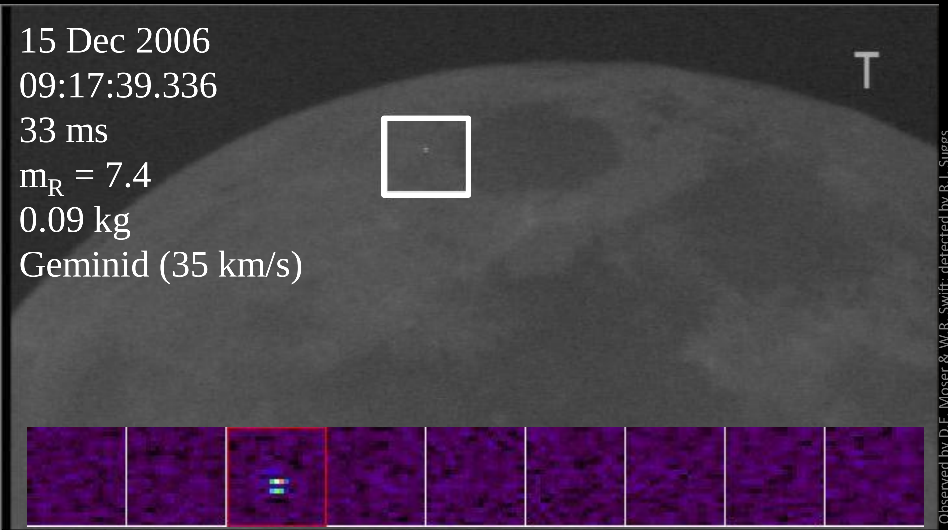
There was enhanced meteor activity in Earth's atmosphere the same night from the Virginid Meteor Complex.

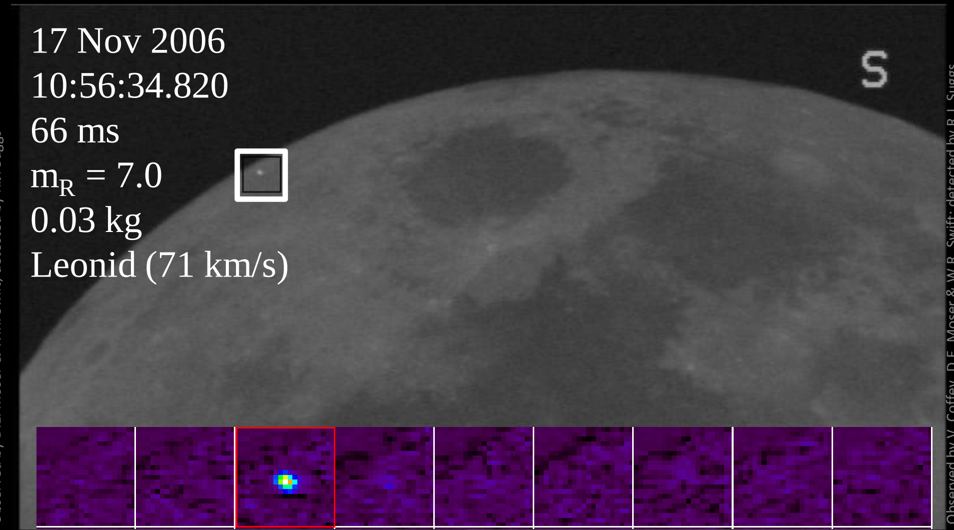
The impact crater associated with the impact flash was found and imaged by Lunar Reconnaissance Orbiter (LRO).

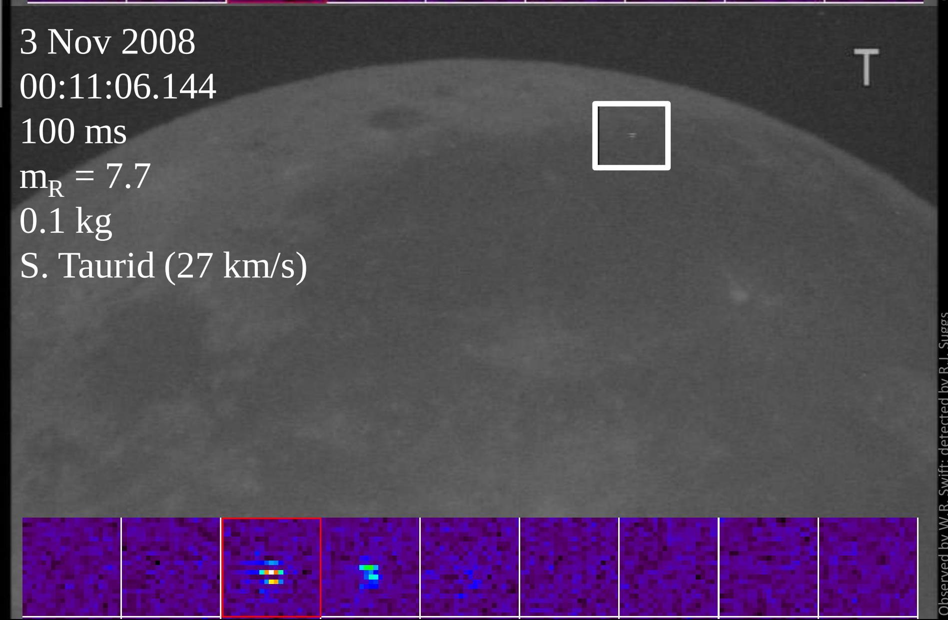
A known crater location provides "ground truth" for testing the geolocation technique.

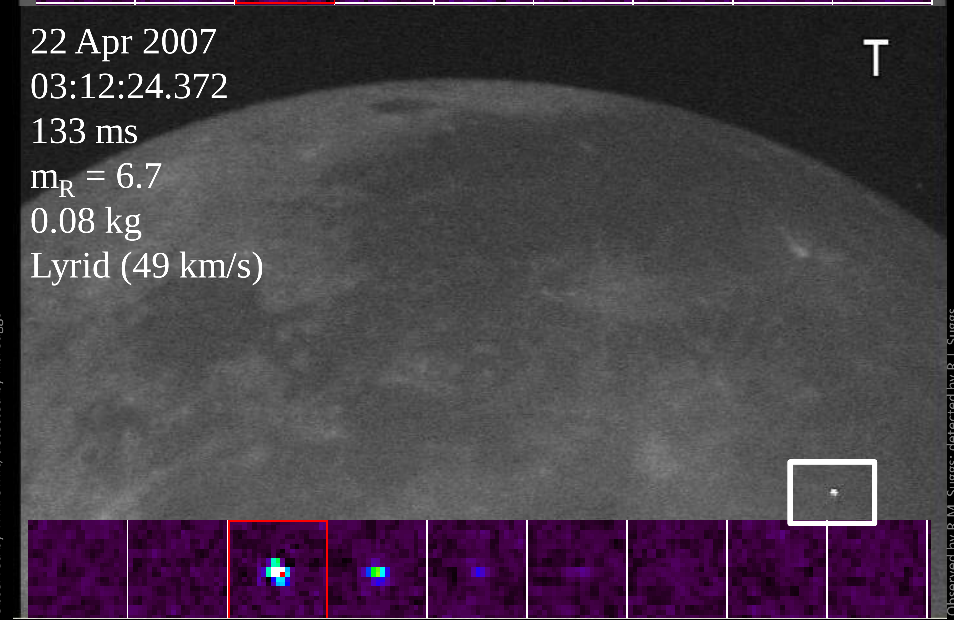
Luminous efficiency estimates can be made by combining flash and crater measurements. A sanity check of photometric procedures and crater scaling relations is also possible.

Typical impact flashes









Atypical flash on 17 March 2013

Observed by A. Kingery & R.M. Suggs; detected by R.J. Suggs

Flash info

Detected with two 0.35 m telescopes

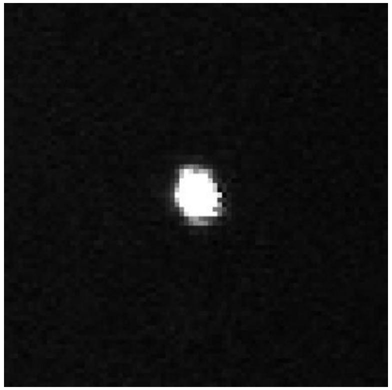
Watec 209H2 Ult monochrome CCD cameras

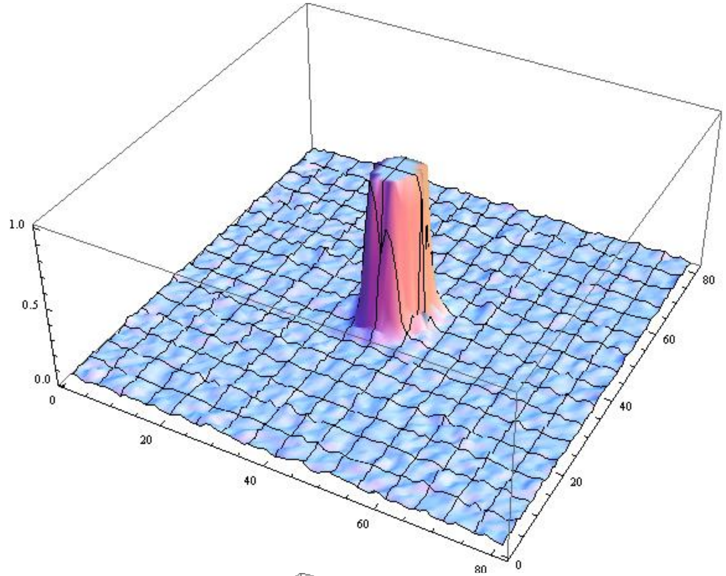
- Manual gain control
- No integration
- $\Gamma = 0.45$

Interlaced 30 fps video

Saturated → needed saturation correction!

Peak R magnitude saturation correction

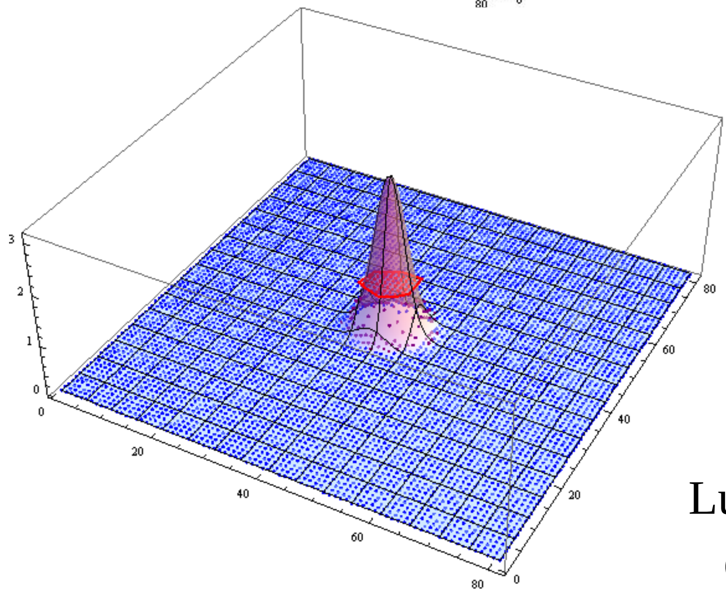




Saturated

Peak m_R = 4.9

UNDERESTIMATED!



Photometry performed using comparison stars
(see Suggs et al. 2014)

CORRECTION:

2D elliptical Gaussian fit to the unsaturated wings

Peak $m_R = 3.0 \pm 0.4$

Luminous energy $= 7.1^{+3.9}_{-2.4} \times 10^6$ J

(Similar results for 2D elliptical Moffat fit)

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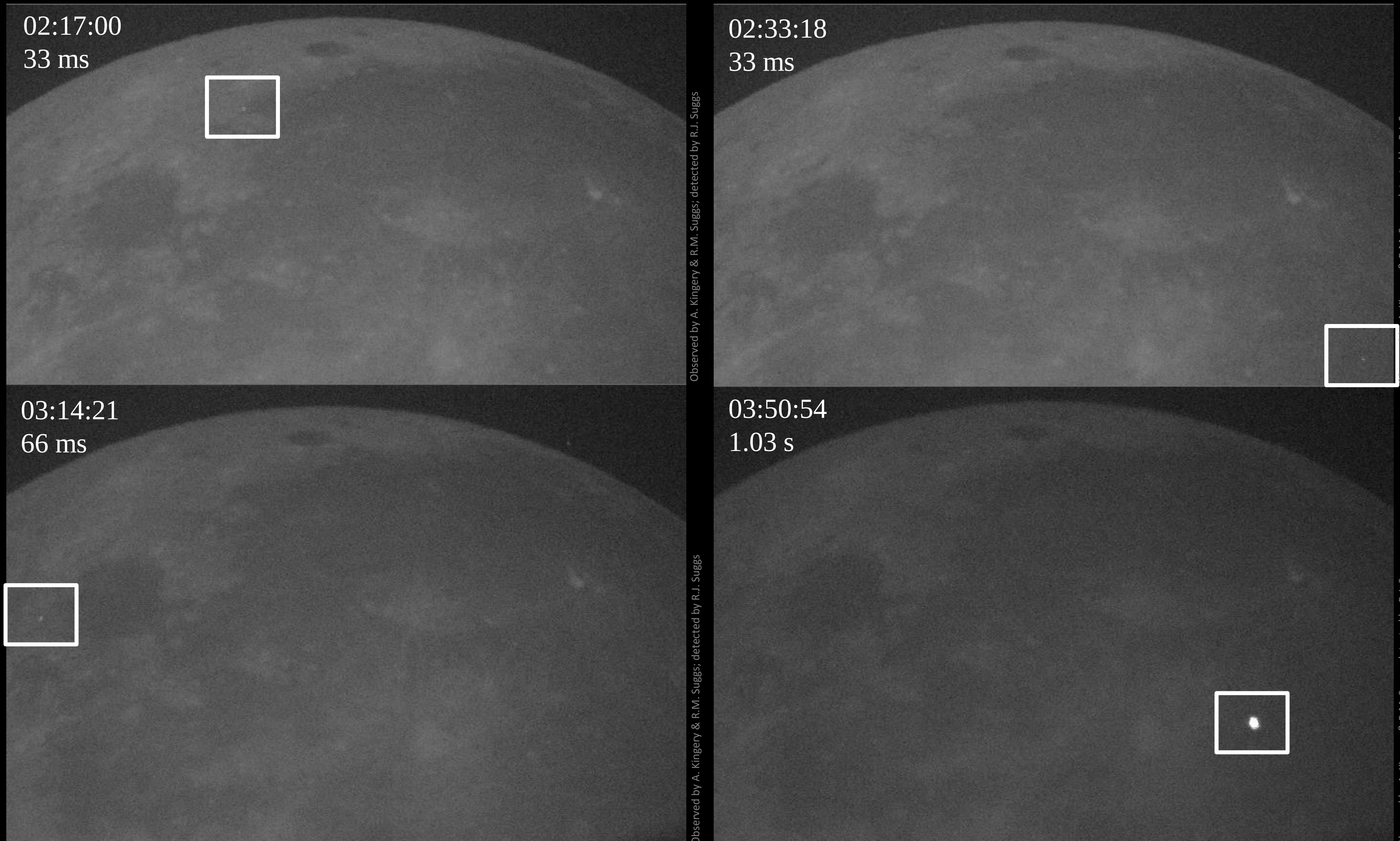
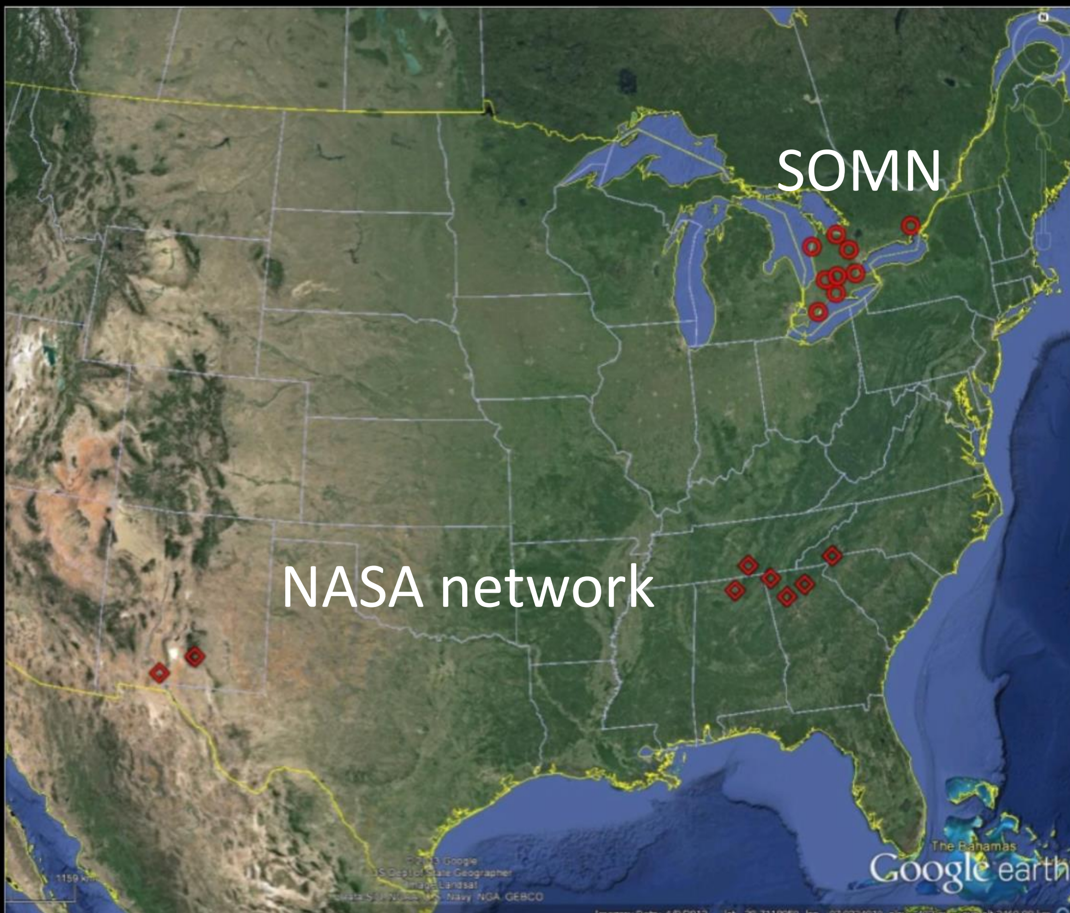
Increased lunar activity on 17 Mar 2013

NASA



Meteor activity on 17 Mar 2013



19 fireballs were observed by NASA & SOMN
all-sky meteor cameras on 17 Mar 2013

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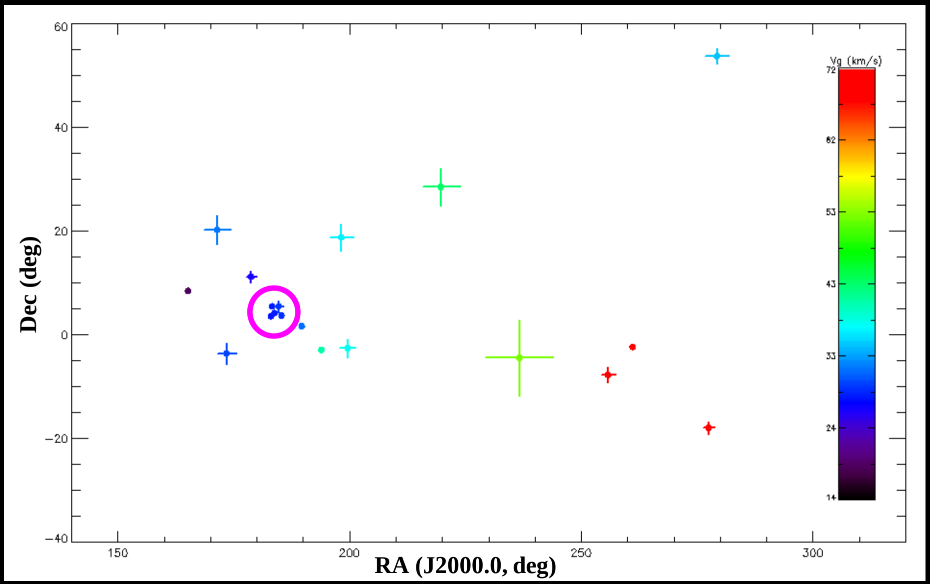
Meteor shower activity on 17 Mar 2013

NASA

19 fireballs seen on 17 Mar 2013



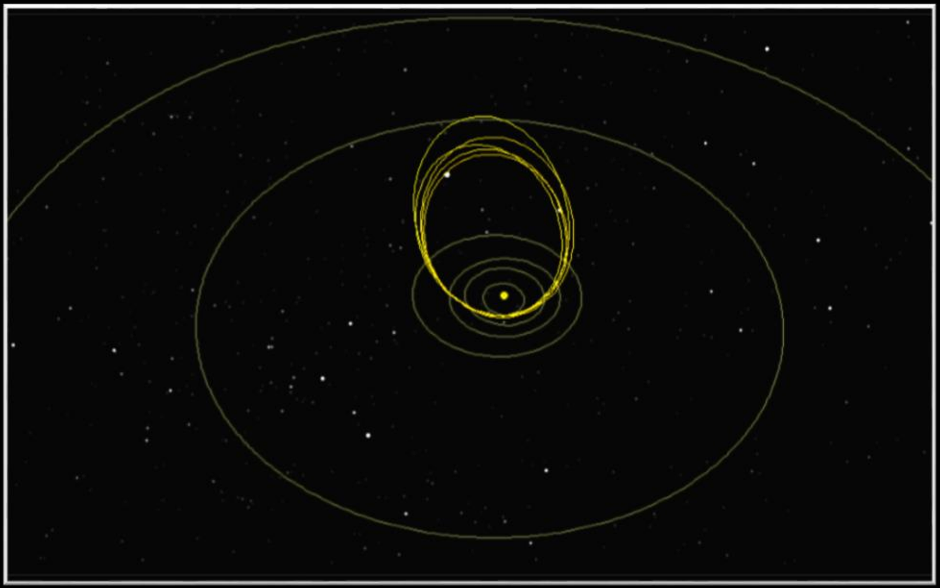
Geocentric meteor radiants color-coded by speed with a tight cluster of 5 with:

Virginid Complex
at λ=356.6

	meteors	NVI[1]	EVI[2]
α_g (°)	184.1 ± 1.0	183.1	181.0
δ_g (°)	4.4 ± 0.9	2.3	4.7
v_g (km/s)	25.6 ± 0.8	23.0	28.9
λ_{sun} (°)	356.6	356.6	356.6

[1]Sekanina (1973), [2]Whipple (1957)

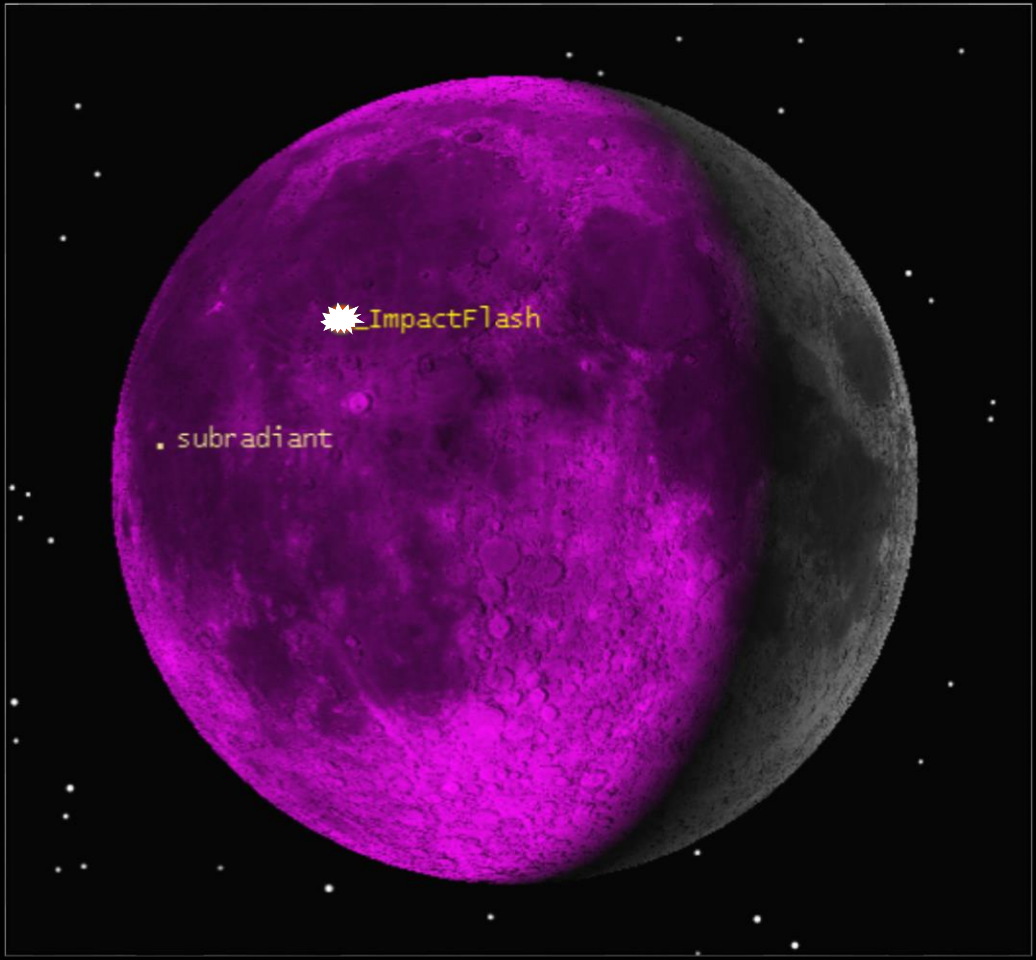
Cluster of 5 seen on 17 Mar 2013



Orbits of the cluster of 5 were very similar with the following average orbital elements:

	meteoroids	NVI	EVI
a (AU)	2.25 ± 0.17	1.69	2.82
e	0.79 ± 0.02	0.71	0.86
i (°)	5.26 ± 1.02	3.7	5.2
ω (°)	280.32 ± 2.11	282.4	285.8
Ω (°)	356.65 ± 0.07	358.0	355.1
q (AU)	0.48 ± 0.02	0.496	0.40
Q (AU)	4.0 ± 0.3	2.89	5.25
Tj	3.1 ± 0.2 ⟶	Indicates ~asteroidal body	

Favorable Virginid radiant geometry



Pink indicates the portion of the moon visible to the radiant.
Impact angle ~56° from horizontal.

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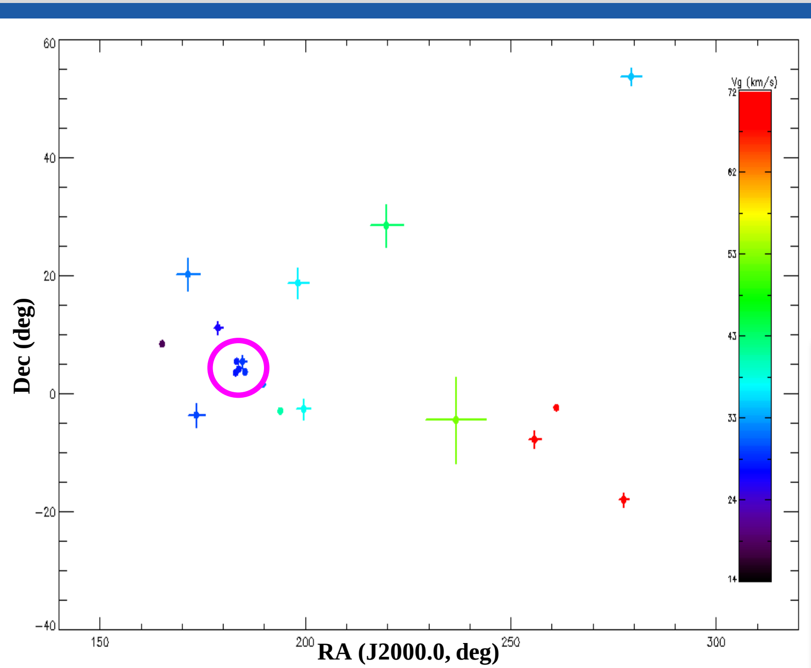
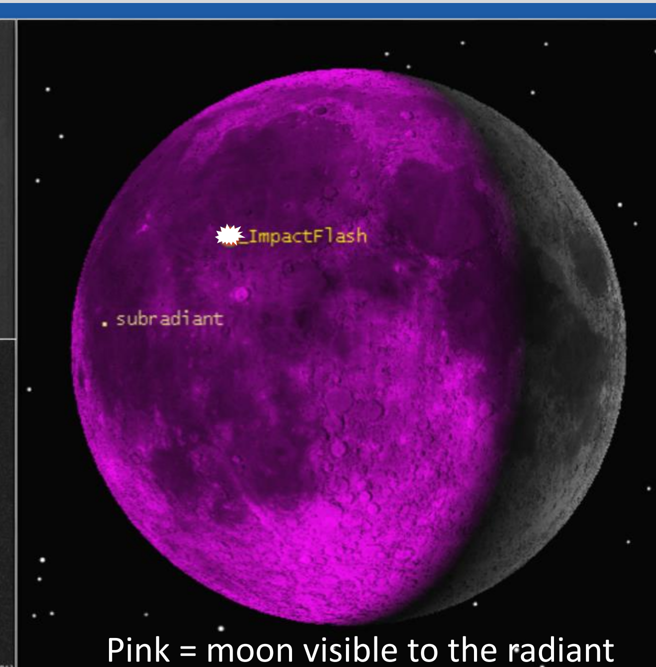
Putting it all together





All-sky meteor cameras detected a deeply penetrating cluster of 5 fireballs on 17 March.

Radiant and orbital elements consistent with the Virginid Meteor Complex (EVI/NVI).

Impact flash rate increased to 1 every 0.87 hours on 17 March. (4 impacts in 3.5 hours)

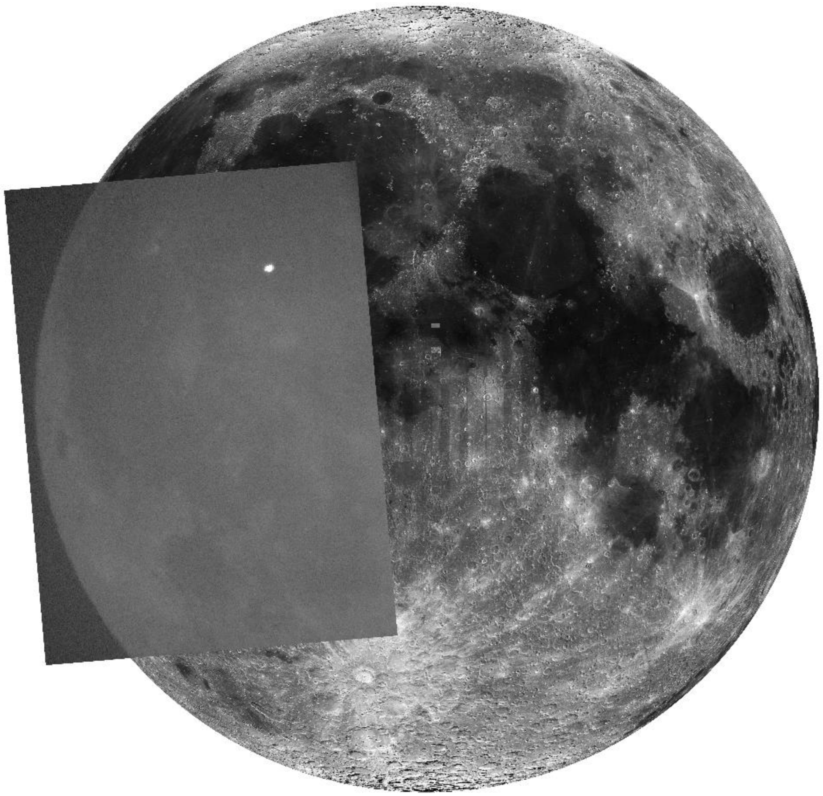
Impact Constraints

Assume impact flash was part of Virginid Meteor Complex

- ➡ v_g = 25.6 km/s
- ➡ θ_h = 56°
- ➡ Asteroidal? (T_j = 3.1 ± 0.2)

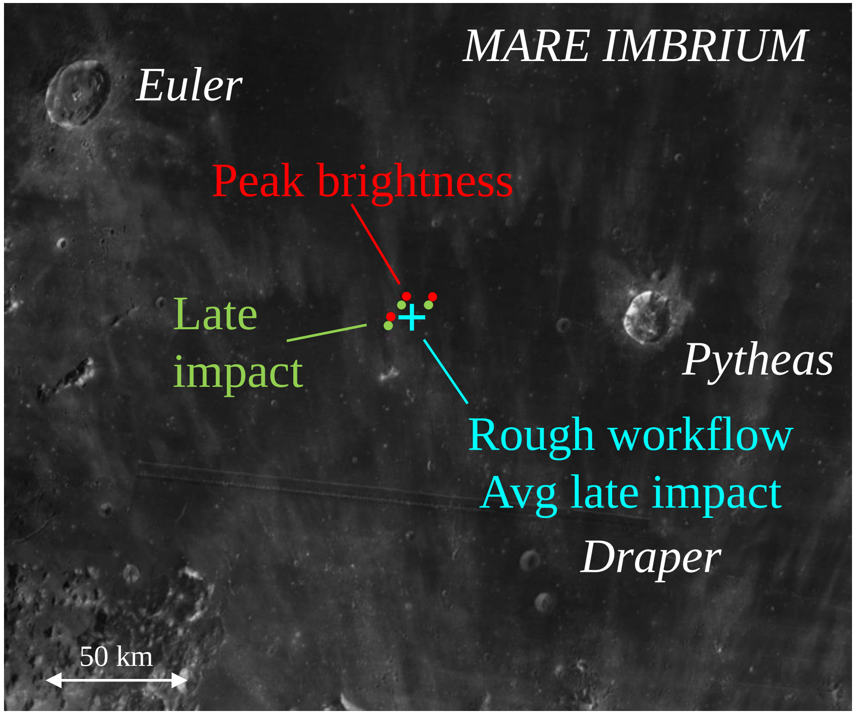
Mapping the impact location
"Rough workflow"

Clementine basemap



ArcMap was used to georeference the lunar impact 3 times, at peak brightness and late impact.

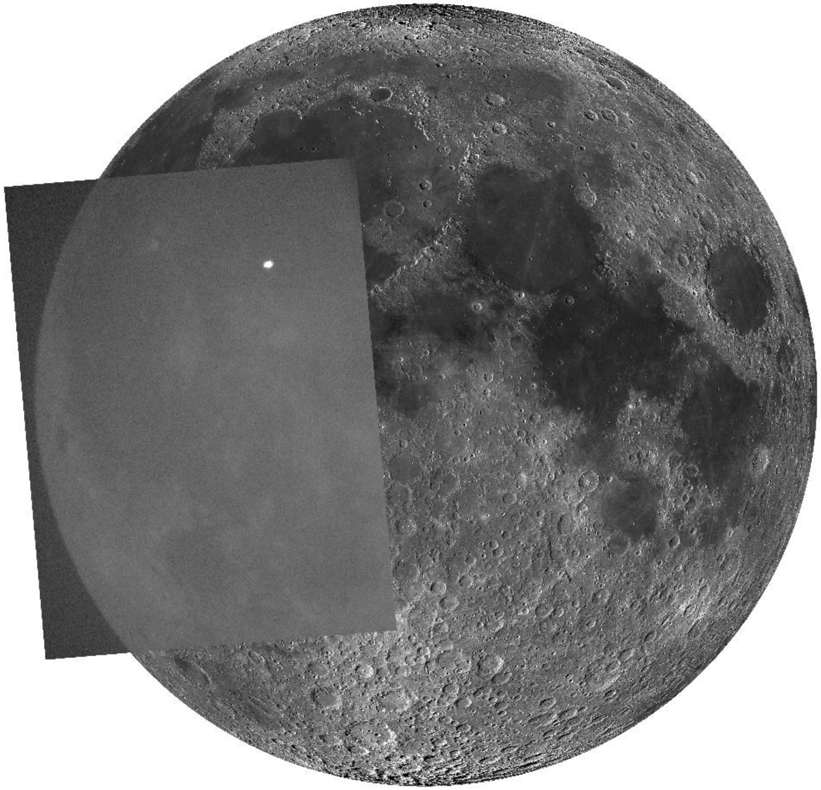
Using the geometric center of the flash



Average predicted crater position 20°.60 ± 0.17 N, 23°.92 ± 0.30 W was sent to LRO.

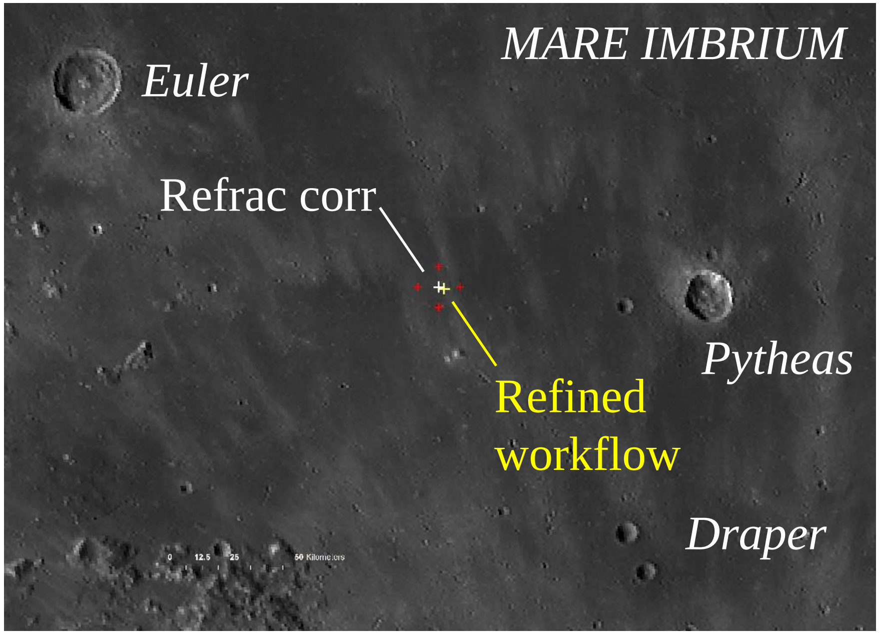
Mapping the impact location
"Refined workflow"

LRO basemap



ArcMap was used to georeference the lunar impact following the geolocation workflow.

Using the intensity-weighted center of the flash



Refined: Nominal predicted crater position
20°.6644 N, 24°.1566 W

Refrac corr: Final predicted crater position
$20°.6842^{+0.2585}_{-0.2581}$ N, $24°.2277^{+0.2881}_{-0.2887}$ W

Impact crater found by LRO!
Robinson et al. (2014)

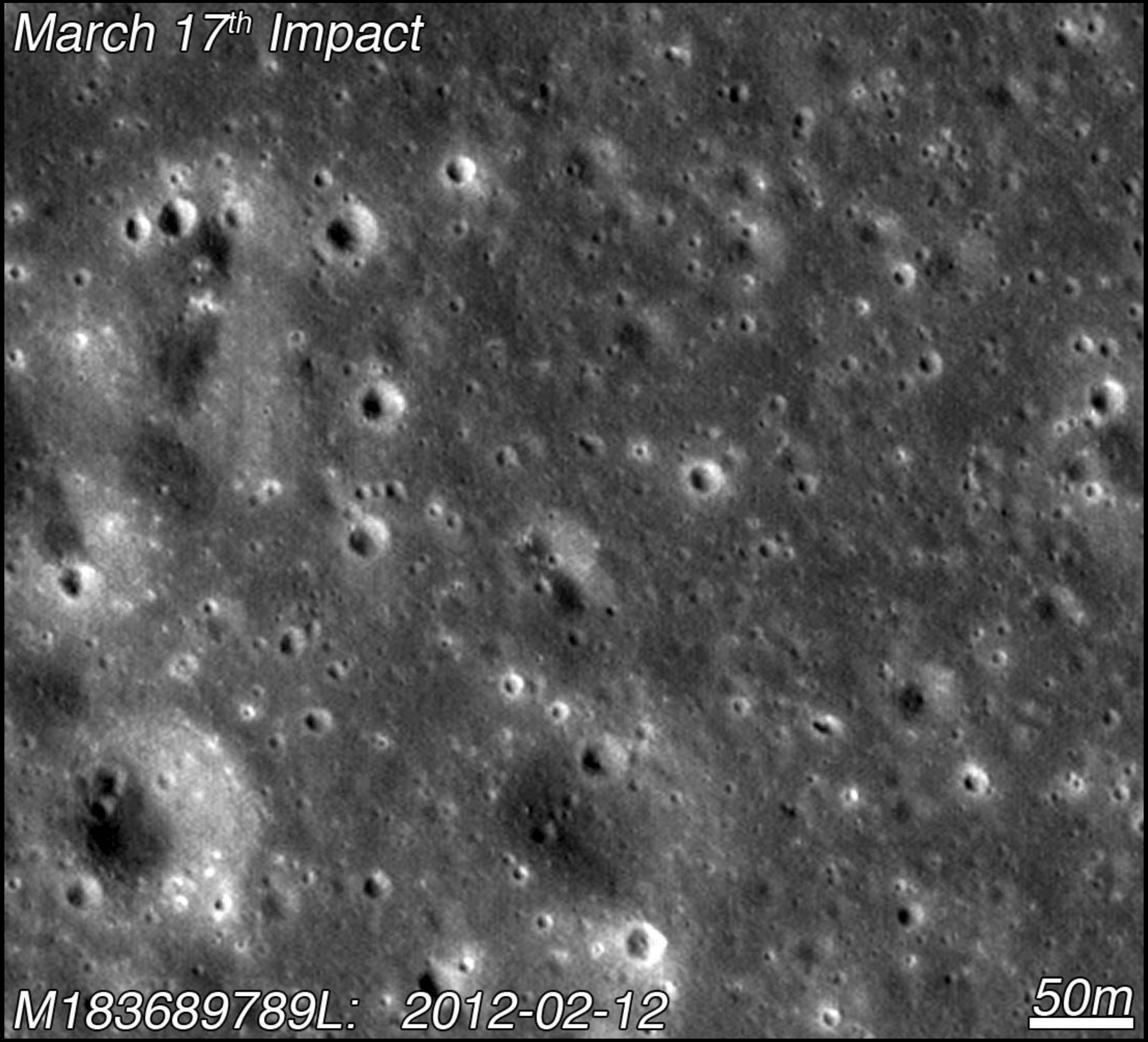


Image from Robinson (2013)
NASA/GSFC/Arizona State University

Features
- Fresh, bright ejecta
- Circular crater
- Asymmetrical ray pattern

Crater info
- Rim-to-rim diameter = 18 m
- Inner diameter = 15 m
- Depth ≈ 5 m

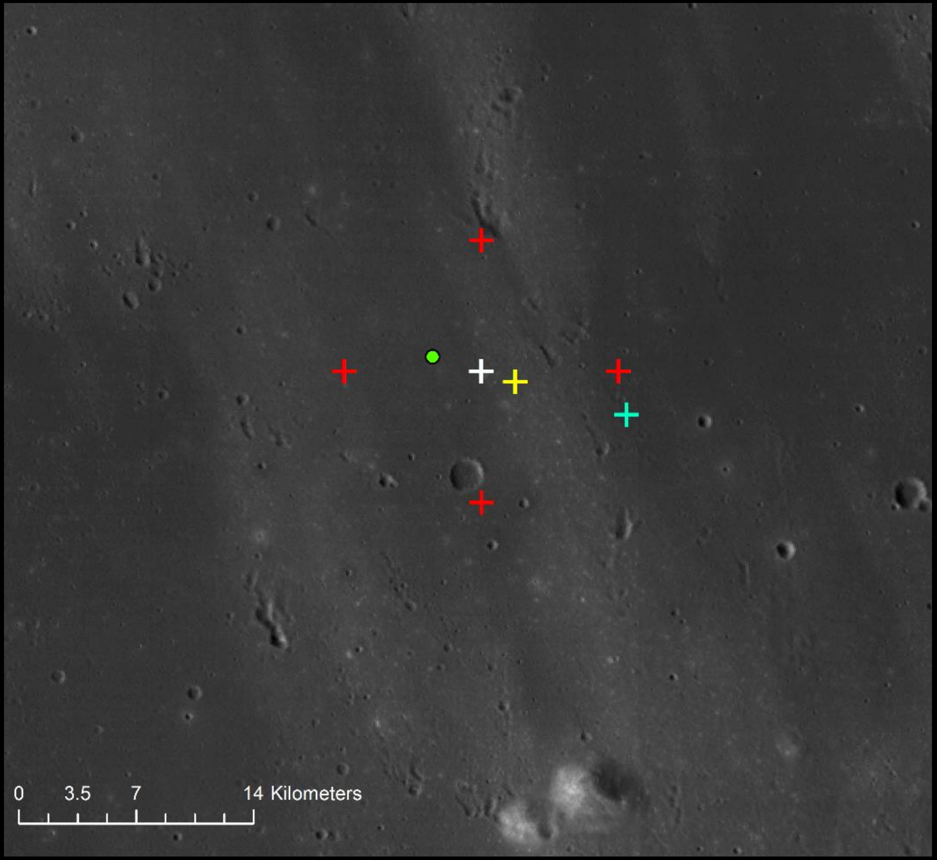
Actual crater location
- 20.7135°N, 24.3302°W

Impact Constraints

➡ Circular crater, impact angle constrained $\theta_h > 15°$

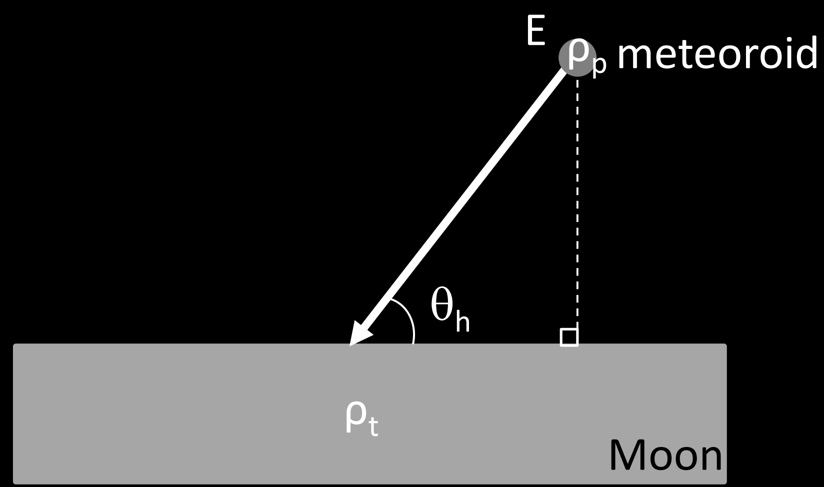
➡ Ejecta gives no azimuth constraint (Robinson, personal comm.)

Comparison of geolocation results to obs crater location



Method	Longitude (° W)	Latitude (° N)	Angular distance from observed (°)	Surface distance from observed (km)
Rough workflow	23.922	20.599	0.39875	12.096
Refined workflow	24.1566	20.6644	0.169665	5.1469
Refined, with refraction correction	$24.2277^{+0.2881}_{-0.2887}$	$20.6842^{+0.2585}_{-0.2581}$	0.100261	3.0415
LRO observed	24.3302	20.7135	-	-

Crater scaling laws



Gault's scaling law (Gault 1974) for D < 100 m

$$D = 0.25\rho_p^{\,0.167}\rho_t^{\,-0.5}E^{0.29}(\sin\theta_h)^{1/3}$$

D = transient crater diameter

ρ_p = projectile density

ρ_t = target density

E = kinetic energy of projectile

θ_h = impact angle measured wrt horizontal

Holsapple crater calculator

(http://keith.aa.washington.edu/craterdata/scaling/index.htm)

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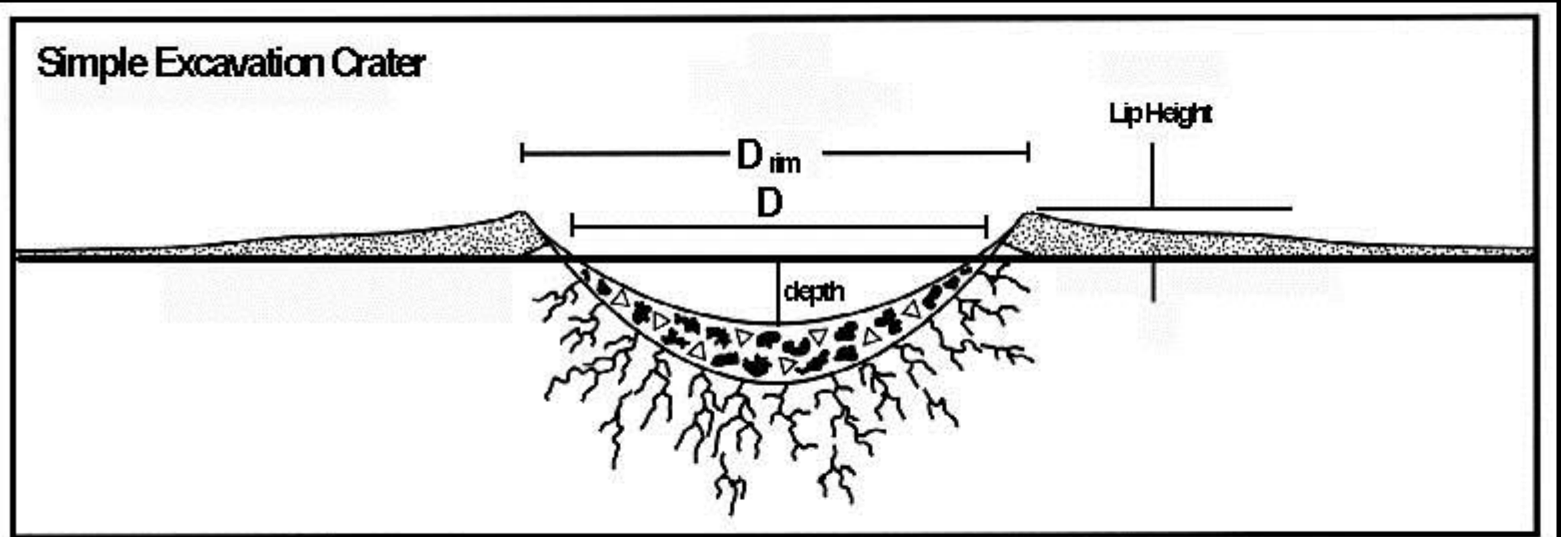
Crater scaling laws



http://keith.aa.washington.edu/craterdata/scaling/index.htm

D

- Transient crater diameter
- Measured at the height of the pre-existing surface
- Aka inner diameter, apparent diameter

D_{rim}

- Crater rim diameter
- Measured from rim to rim
- Aka outer diameter

Holsapple assumes $D_{rim} = 1.3D$ similar to Melosh (1989)

Transient crater diameter estimates

Assumptions: Virginid v_{gfoc}=25.7 km/s, θ_h = 56°; ρ_t = 1500 kg/m^3 (regolith)

Model	Lum eff. η	KE $\times 10^9$ (J)	Mass (kg)	ρ_p (kg/m^3)	D_{calc} (m)	D_{obs} (m)	% Err
Gault's crater scaling law (Gault 1974)	5×10^{-4} (Bouley et al. 2012)	14 [9.4,22]	42 [28,66]	1800	18.5 [16.5,21.1]	15	23%
				3000	20.2 [18.0,23.0]	15	35%
	1.3×10^{-3} (Moser et al. 2011)	5.4 [3.6,8.4]	16 [11,26]	1800	14.1 [12.5,16.0]	15	6%
				3000	15.3 [13.6,17.4]	15	2%
Holsapple's online calculator (Holsapple 1993)	5×10^{-4}	14 [9.4,22]	42 [28,66]	1800	12.2 [10.9,13.8]	15	19%
				3000	12.5 [11.1,14.2]	15	17%
	1.3×10^{-3}	5.4 [3.6,8.4]	16 [11,26]	1800	9.3 [8.3,10.5]	15	38%
				3000	9.5 [8.5,10.8]	15	37%

Two example values of η from the literature yield large ranges for KE and mass. Consequently, model results are highly dependent on luminous efficiency η.

Assuming a velocity dependent $\eta = 1.3\times10^{-3}$, these model results are consistent with the observed crater diameters.

D_{calc} = 8-18 m transient crater
D_{calc} = 10-23 m rim-to-rim

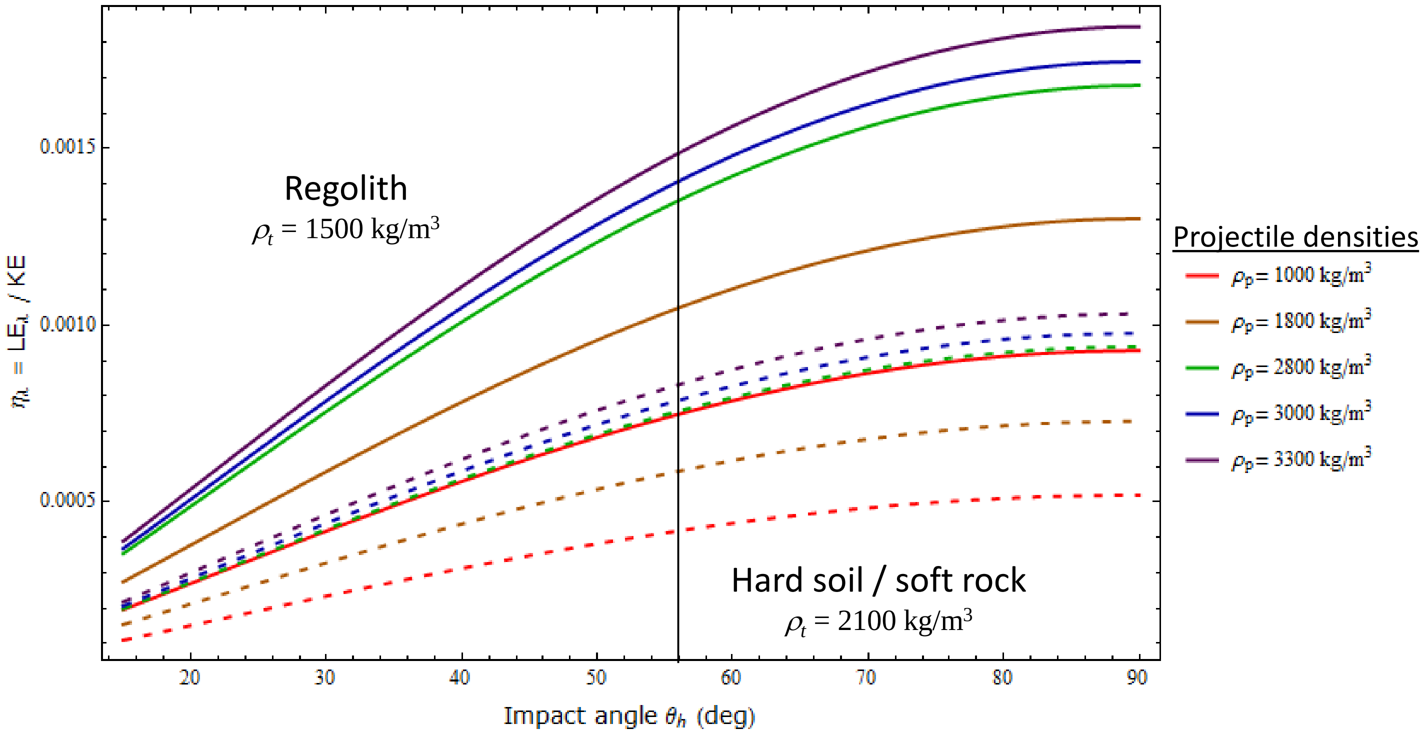
D_{obs} = 15 m inner ('transient')
D_{obs} = 18 m rim-to-rim

Luminous efficiency: $LE_\lambda = \eta_\lambda KE$

D_t = 15 m from crater measurements
$LE_\lambda = 7.1 \times 10^6$ J from flash measurements

Gault's crater scaling law (Gault 1974) rearranges to give η_λ vs θ_h without assuming impact speed.

$$\eta_\lambda = LE_\lambda / KE = LE_\lambda / (4.0\, D_t\, \rho_p^{-0.167}\, \rho_t^{0.5} \sin^{-1/3}\theta_h)^{1/0.29}$$



Typical values of η_λ derived from lunar regolith range from $2 \pm 1 \times 10^{-4}$ to $2 \pm 1 \times 10^{-3}$.

Assuming association with the Virginids, $\theta_h = 56°$ and $7.5^{+4.5}_{-2.5} \times 10^{-4} < \eta_\lambda < 1.5^{+0.8}_{-0.5} \times 10^{-3}$.

Impact summary

Date of impact:	17 March 2013 3:50:54 UTC
Duration of impact:	1.03 s
Corrected flash peak R magnitude:	3.0 ± 0.4
Luminous energy generated by impact:	$7.1^{+3.9}_{-2.4} \times 10^6$ J
Estimated kinetic energy of impactor:	$5.4^{+3.0}_{-1.8} \times 10^9$ J = 1.3 tons of TNT (assuming $\eta = 1.3 \times 10^{-3}$)
Estimated mass of impactor:	16^{+10}_{-5} kg (assuming v = 25.7 km/s)
Estimated diameter of impactor:	22 ± 3 cm (assuming $\rho_p = 3000$ kg/m^3)
Crater diameter:	18 m rim-to-rim, 15 m inner ('transient')
Crater location:	20.7135° N, 24.3302° W
Possible meteor shower association:	Virginid Meteor Complex

Backup Slides

References

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Ejecta distribution
after Robinson et al. (2014)

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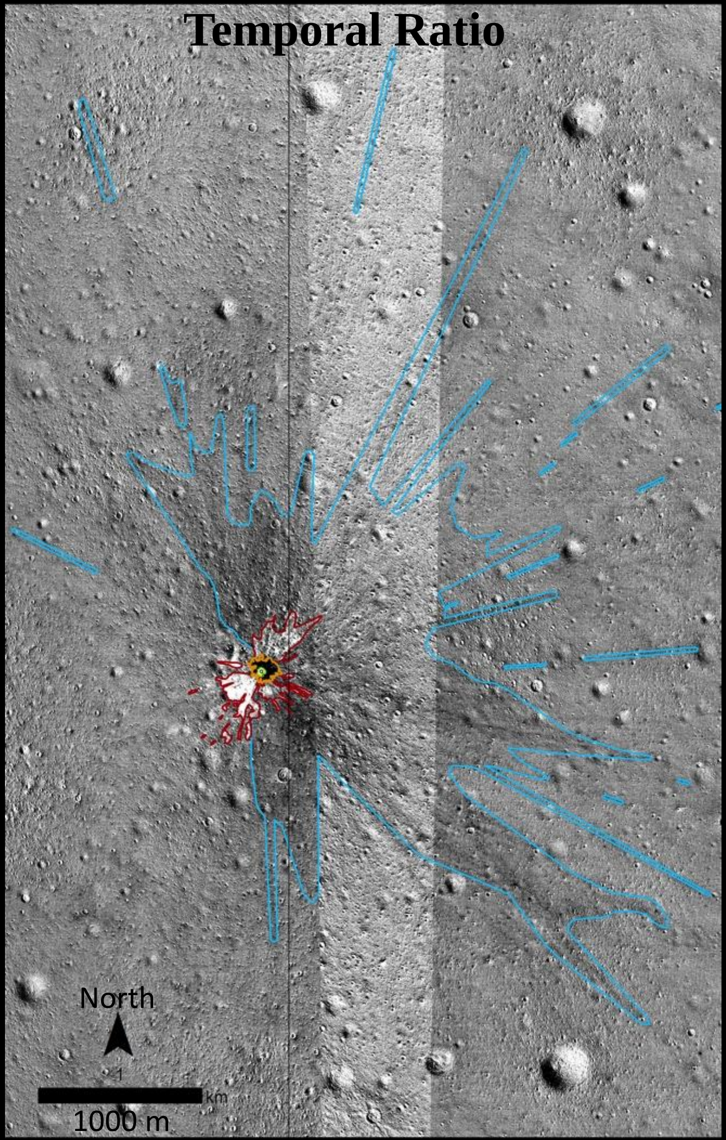

Robinson et al. (2014)

Ejecta in multiple reflectance "zones"

High reflectance zone 10-20 m SW, <10 m NE
Low reflectance zone 50 m WSW, 80 m ENE
High reflectance zone ~300 m rough semicircle
Low reflectance zone ~1 km centered in NE
248 circ/irreg splotches within 30 km

See Robinson et al. (2014) for more details

Impact Constraints

➡ Circular crater, impact angle constrained >15°

➡ HRZ – impact possible from SE or NW
LRZ – impact possible from SW
∴ no azimuth constraint (Robinson, personal comm.)

An impact from the SW is consistent with an impactor from the Virginid Meteor Complex.